Measuring and Monitoring Electronic Properties of Si During Industrial Material Preparation and Cell Fabrication.

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ABSTRACT

A family of new diagnostic techniques incorporating the quasi-steady-state measurement of minority-carrier lifetime and illumination-V_{oc} curves has recently become very common in R&D laboratories worldwide. Efforts are now under way to optimize these techniques and measurement instruments for industrial applications in the process line. Examples of these advances are described here including measurement of minority-carrier lifetime in Si boules, blocks, and wafers, and the fast determination of illumination–Voc curves at intermediate steps in the fabrication process.

1. Introduction

A number of new techniques for characterization, diagnostics, and process control for silicon solar cells have come into widespread use in the last 5 years. These include two techniques developed by Sinton Consulting for the electronic characterization of wafers and solar cell precursors.

The first technique is the Quasi-steady state (QSS) lifetime measurement[1]. This instrument illuminates a wafer with a slowly varying light intensity from a flashlamp. During the course of a single flashlamp pulse, typically 20 ms long, the lifetime vs. minority-carrier injection level is determined over a wide range of minority-carrier densities. The use of QSS measurements in addition to more traditional photoconductance decay measurements allows complementary simple measurement of very low lifetimes. The steady-state scan also permits corrections for trapping effects that frequently occur in multicrystalline wafers. An implementation of this technique with an instrument using contactless eddy-current sensing of the photoconductance (2) has been applied to studies of surface passivations, emitter diffusions, bulk lifetime and defect studies. Nearly 100 technical publications detail these research results. These publications and this experience provides a resource base for applying these techniques into simple, yet sophisticated process control and monitoring applications on production lines.

A second technique, illumination-V_{oc} measurements, allows characterization of a solar cell precursor as soon as the junction is present in the solar cell. By probing the n+ and p+ regions, an illumination-Voc curve can be obtained that indicates the upper bound for the possible solar cell performance[2]. Through the latter stages of the process, especially metallization firing, these characteristics can be monitored to evaluate the effects of nitride, shunts, and poor contact formation on the solar cell. Once the cell is finished, a comparison of this curve with the conventional IV curve indicates the series resistance without ambiguity.

2. Minority Carrier Lifetime Measurements.

An industrial version of the R&D lifetime-test instrument has been developed. This new instrument uses a small sample head in place of the large stage on the R&D table-top version. A photo of this configuration is shown in Fig. 1.

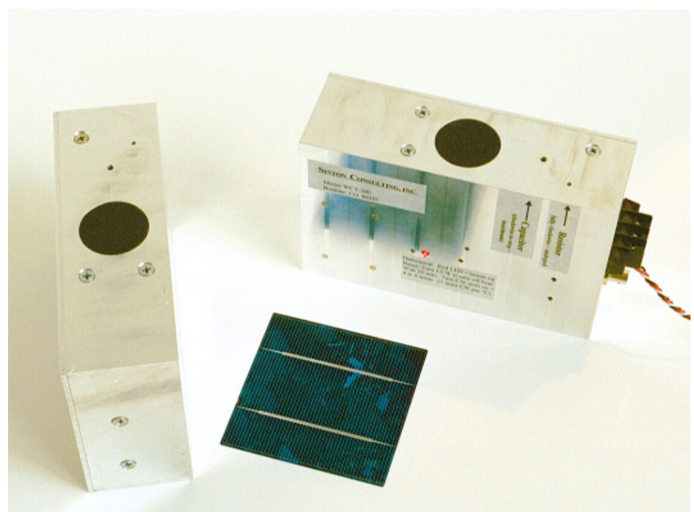


Fig. 1. A small sample-head version of a contactless minority-carrier lifetime measurement tool. The black area indicates the one configuration of the sensor area. The instrument can be used with top illumination or through-the-instrument illumination.

This instrument is being testing in various configurations for several applications as describe below.

Measurement of Boules and MultiX blocks.

An application of the instrument for measuring silicon boules is shown in Fig. 2. Standard measurements on the relatively heavily doped silicon used for solar cells are difficult at the stage of boules. At the same time, previous studies have shown these measurements to be very useful (3).

Fig. 2. A measurement setup with through-the-instrument illumination suitable for measuring boules.

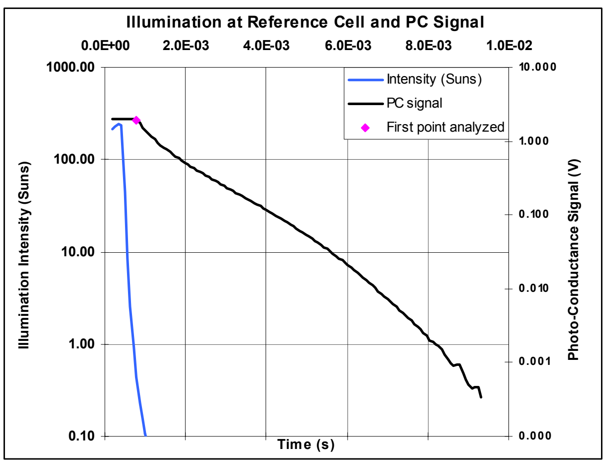


Fig. 3. Data from the setup in Fig. 3. For this long-lifetime sample, transient photoconductance analysis was used.

Data shown in Fig. 3 and Fig. 4.for a 1.6-Ohm-cm p-type silicon boule section. The analyzed data, shown in Fig. 4 shows a peak lifetime of 1.4 ms. The injection level dependence at lower carrier densities is evident from this data. The lower measured lifetime at high carrier densities is due to surface recombination early in the pulse before the photoconductance near the surface decays away. This is a well-known effect of PCD measurements on samples with unpassivated surfaces. The magnitude of the effect was simulated for this instrument and configuration. A simulation of the measured lifetime is shown in Fig. 5. Measurements on silicon boules will yield lower bounds on the actual lifetime. However, at long times after the initial pulse, the measured lifetime asymptotically approaches the actual lifetime.

Another application for lifetime testing in a production setting is the measurement of Multicrystalline blocks.

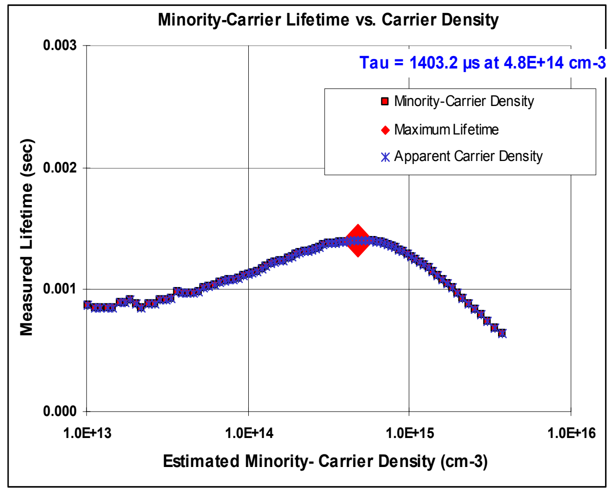


Fig. 4. Lifetime vs. approximate minority-carrier density for a 1.6 Ohm-cm p-type silicon boule section. (Sample provided by Jan Vedde, Topsil).

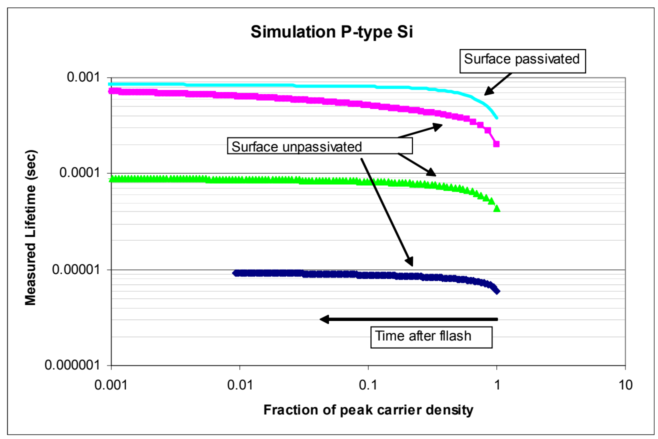


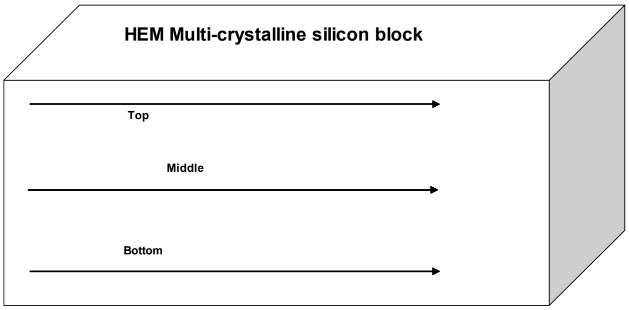
Fig. 5. A PC1D[4] simulation of the photoconductance decay measurement for a 1 ohm-cm p-type silicon boule.

Often, it is desired to scan these blocks to identify the regions that are suitable to saw into wafers. Data from line scans for a HEM multicrystalline block are shown in Fig. 6.

Measurement MultiX wafers.

The vast majority of reported data from QSS lifetime test instrument has been for wafers in the R&D laboratories. In these cases, often the samples are designed to be measured. If the study is on bulk lifetime, a nearly perfect nitride passivation can be applied to the wafer so that the measured lifetime accurately indicates bulk lifetime. If the study is on surface passivation, then nearly perfect FZ wafers can be used in order that the measurement indicates surface properties.

Practical industrial applications have different requirements. For example, it is often desirable to know if the wafers that have just been purchased are of high quality. In an industrial setting, it is best if no surface preparation is required in order to determine this. It is difficult, though possible, to provide some information on wafer quality even on unpassivated wafers.



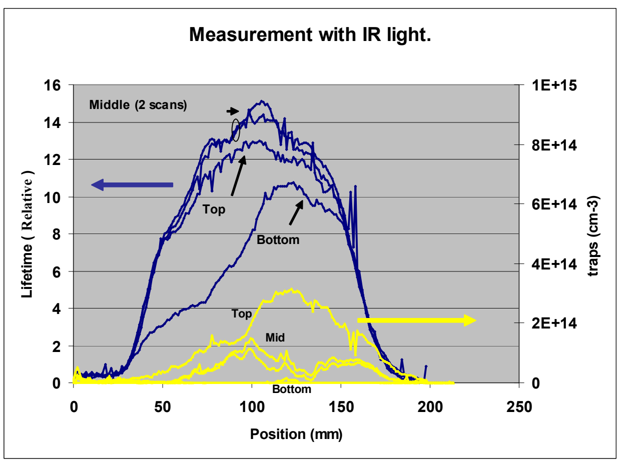


Fig. 6 Line scans from a multicrystalline block of silicon, indicating lifetime, and trapping vs. position in the block. (Sample courtesy Keith Matthei, GT Solar).

Fig. 7 shows a simulation for an industrially-relevant 300 micron-thick 1-Ohm-cm p-type silicon wafer. The measured lifetime is shown as a function of surface recombination velocity (for unpassivated wafers), emitter saturation current density (for dopant diffused wafers) and wavelength of incident light used during the QSS lifetime measurement.

This type of analysis is guiding the development of in-line lifetime measurement tools to address the relevant industrial process-control issues.

For example, from this plot, it is evident that a measured lifetime of 2 µs using 1000 nm light on an unpassivated wafer can be used to indicate that the lifetime is at least 2 µs. However, if the surface recombination velocity is know to be repeatable, and greater than 3e4 cm/s, then this measured lifetime of 2µs actually indicates a 10µs bulk lifetime. Data from typical unpassivated surfaces for 1 Ohm-cm p-type silicon seems to indicate 5E4 cm/s, although more work is required to determine this figure

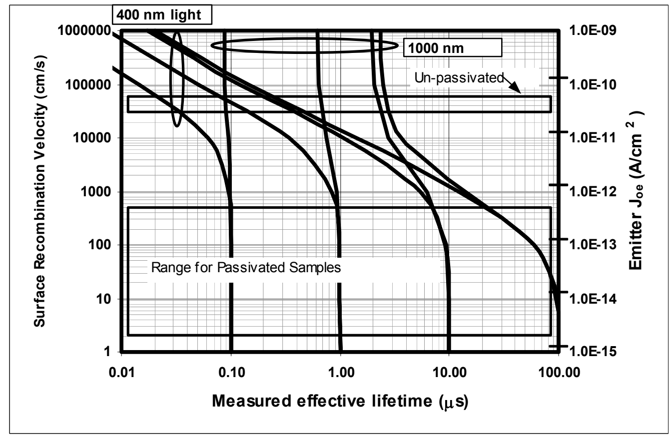


Fig. 7. A PC1D simulation for the lifetime measured by a QSS photoconductance measurement as a function of wavelength, and surface passivation.

for the general case. Figure 7 indicates that he surface recombination and bulk lifetime can be unambiguously determined by using 2 wavelengths of light. Studies are underway to use these effects in order to optimize an industrial tool for this application by using these effects.

Another interesting question when dealing with multi-X wafers how to interpret the lifetime as measured from a wafer where each grain has a unique lifetime.

Studies are being performed to address this issue. Many industrial users of these instruments have found that lifetime measurements directly after phosphorus diffusion are very predictive of the final cell results [5]. With respect to multicrystalline wafers, this brings up an interesting point. After the phosphorus diffusion, all of the grains are connected in parallel, just as in the final solar cell, but with a relatively high series resistance provided by the dopant diffusions and the lateral substrate resistance.

Does this physical boundary condition effectively average the lifetime data in the relevant way to give good predictive results?

A study of this effect will be presented at the World Conference in Osaka. Fig. 8 shows the key result. Taking a model case of 40% of the area being “bad grains” and 60% good grains, the equipotential across the solar cell is maintained if the bad grains are small. This indicates that the measured lifetime would correspond to the case where the entire cell is maintained at constant voltage. This is the relevant case. However, if the bad grains are large, or the illumination intensity is high, then the dopant diffusions can’t maintain a constant voltage across all of the grains. The bad grains have a lower voltage. In the limit of large grains or high intensity, the QSS method measures the area-weighted average of the minority carrier effective lifetime.

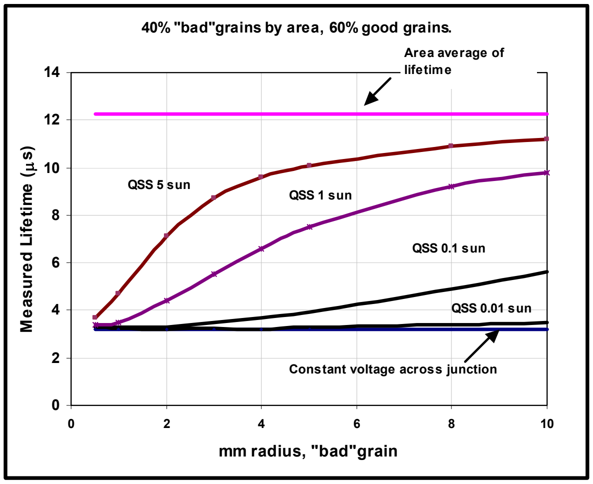


Fig. 8. A model simulation of the lifetime that will be measured for a mix good and bad grains across a multicrystalline wafer.

2. Voltage Measurements.

The other technique being investigated in this work for application to production is the measurement of I-V curves on solar cell precursors.

These curves, actually illumination-Voc curves, can be obtained directly after the phosphorus diffusion, and indicate the upper bound on the efficiency possible for that solar cell. The curve is take at open-circuit conditions. Therefore, it has no series resistance. The illumination-Voc curve is shifted by the assumed short-circuit current in order to present the data in the well-understood standard format for an illuminated IV curve. One of these curves is shown in Fig. 9.

This data is especially useful in evaluating the material quality and the surface passivation quality. Then, the results can be tracked through the metallization firing in order to comprehensively evaluate the effects of hydrogenation on the cell, as well as the series resistance and shunt effects due to the back –end processing.

Do date, the technique has been implemented using fast electronics and data analysis in order to achieve a measurement rate of one wafer each 2 seconds, as indicated in Fig. 10.

Acknowledgements.

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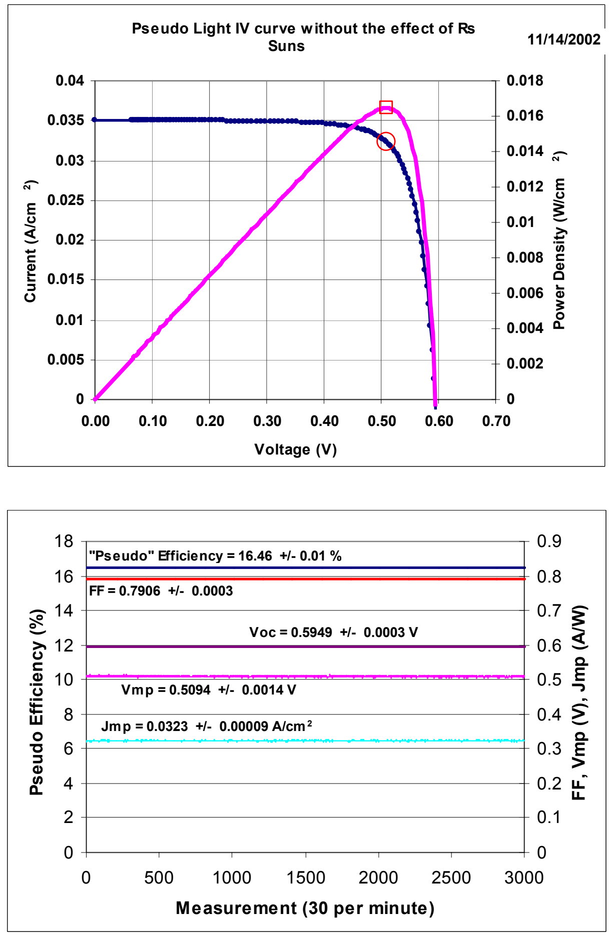

Fig. 10. An illumination-V_{oc} curve (top). Data logged at a rate of 30 cells per minute (bottom).

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